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A COMPARISON OF AVAILABILITY CENTERED INVENTORY MODELS USING THE TIGER SIMULATION PROGRAM

by

Paul D. Huscher

March 1988

Thesis Advisor: W. M. Woods

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Developing and updating shipboard repair part allowances for the tremendous number of Navy shipboard equipments is a large scale, complex task. In order to avoid excessive downtime on these critical equipments, more sophisticated allowance computation techniques which account for system characteristics and availability requirements are needed. This study examines three availability centered inventory models used to determine repair part allowances. The models are the Availability Centered Inventory Model (ACIM), the Lagrangian Equipment Optimization (LEO) model, and the Spares Economically and Automatically Selected to Criteria Applied for Performance Effectiveness (SEASCAPE) model. Model effectiveness will be compared using a hypothetical ship steering system. After inventory levels are computed by each of the models through internal optimization techniques, operational availability (A_o) is estimated by simulation of a ship's mission timeline using the Naval Sea Systems Command's TIGER program. The comparison is made by examining the availability of the hypothetical system using the TIGER model under the following conditions: fixed budget, variable budgets, and variable mean supply response times (MSRT).

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A Comparison of Availability Centered Inventory Models
Using the TIGER Simulation Program

by

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ABSTRACT

Developing and updating shipboard repair part allowances for the tremendous number of Navy shipboard equipments is a large scale, complex task. In order to avoid excessive downtime on these critical equipments, more sophisticated allowance computation techniques which account for system characteristics and availability requirements are needed. This study examines three availability centered inventory models used to determine repair part allowances. The models are the Availability Centered Inventory Model (ACIM), the Lagrangian Equipment Optimization (LEO) model, and the Spares Economically and Automatically Selected to Criteria Applied for Performance Effectiveness (SEASCAPE) model. Model effectiveness will be compared using a hypothetical ship steering system. After inventory levels are computed by each of the models through internal optimization techniques, operational availability (A_o) is estimated by simulation of a ship's mission timeline using the Naval Sea Systems Command's TIGER program. The comparison is made by examining the availability of the hypothetical system using the TIGER model under the following conditions: fixed budget, variable budgets, and variable mean supply response times (MSRT).

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I. INTRODUCTION

A. PROBLEM STATEMENT AND BACKGROUND

Fleet readiness is essential to the United States Navy's ability to conduct its many missions. In 1981, by direction of the Chief of Naval Operations (CNO), Naval Material Command Instruction (NAVMATINST) 3000.2 [Ref. 1] established operational availability (A_o) as the "primary measure of material readiness" for naval weapon systems and equipment.

The operational availability (A_o) of a system is the probability that the system is ready to perform its specified function at any random point in time. The term "system" will be used throughout this thesis to mean a repairable set of equipment designed to perform a specified function.

The Navy is interested in maximizing the A_o of naval weapons systems and equipments because fleet readiness is directly related to the achievement of A_o thresholds established by the Chief of Naval Operations (CNO). A system A_o threshold is the level of A_o required for the system to meet an assumed threat. Spare parts are essential in maintaining a high level of A_o for ships in the fleet because even highly reliable equipment will fail over time. Repairing equipment, usually means replacing defective components with spare components. These spare components are held either onboard or must be obtained from off ship.

Given the long resupply times involved in obtaining parts from off ship, A_o will be increased if more parts, and particularly those most likely to fail, are stocked onboard. However, budget and space constraints limit the inventory that can be stocked. Consequently, stocking policies are needed that attempt to keep the fleet operating efficiently by achieving and maintaining A_o thresholds and still meet its inventory cost and space constraints.

One of the Navy's attempts at developing shipboard repair part allowances was the Fleet Logistic Support Improvement Program (FLSIP). FLSIP computes ship repair part allowances based primarily on projected demand for a 90-day period plus insurance quantities for mission-essential parts in vital equipment.

Due to the inherent reliability of most equipment, FLSIP usually provides adequate repair part support. However, for some critical, complex shipboard equipments the simple FLSIP rules appear to be inadequate. For example, in 1983 a review

of equipment availability indicated that "certain critical equipments had excessive downtimes due to a lack of on-hand repair parts. This state of affairs existed even though supply support standards (about 125 hours average parts delay) were generally being met. The reason this occurs is because standard supply policy does not adequately support some complex systems which have mean time between failures (MTBF's) of 500 hours or less" [Ref. 2: p. 33]. In order to avoid excessive downtime on these critical equipments, more sophisticated allowance techniques which account for system characteristics and availability requirements were needed. To fill this need, the CNO directed that a sophisticated availability-based sparing technique be developed and applied on a selected basis for equipments which require a level of readiness above that which standard policies can provide.

In response to that direction, the Chief of Naval Material (CHNAVMAT) recommended a standard availability centered optimization model for use by all program managers in determining consumer level stockage quantities for selected equipments. This model is known today as the Availability Centered Inventory Model (ACIM). It develops repair parts allowances to achieve a specified A_o at minimum possible inventory cost. Since CHNAVMAT's disestablishment, the Naval Supply Systems Command (NAVSUP) has assumed responsibility for the availability based inventory models.

B. SCOPE AND PURPOSE

The author became aware of the Navy's problem of conflicting measures of effectiveness for logistic support during an operations research experience tour sponsored by OPNAV 91 in Washington, D.C. during May and June of 1988. While on experience tour Dr. Patrick Hartman from Naval Sea Systems Command's (NAVSEA's) maintainability and reliability branch and Mr. Frank Strauch from Fleet Material Support Office (FMSO) in Mechanicsburg, Pa. discussed areas of current research. They suggested using NAVSEA's TIGER program to compare existing availability based inventory models. NAVSEA and FMSO are interested in this research because it gives them an external source which can be used as a point of comparison for their research findings.

This study compared the Availability Centered Inventory Model (ACIM), the Lagrangian Equipment Optimization (LEO), and the Spares Economically and Automatically Selected to Criteria Applied for Performance Effectiveness (SEASCAPE) models. Prior to model comparison, each of the three models was validated by running sample input data through each model. The outputs were then compared for accuracy

against sample outputs also provided by FMSO with each model. All three models were successfully validated in this way.

A hypothetical ship steering system was used as the system for which the sparing outputs of the three models would be evaluated. The steering system consists of eight different parts. There are multiple numbers of some of these parts making a total of fourteen individual parts in the system. Two different configurations of the system were used. The first configuration arranged all fourteen components in series. In the second configuration the parts are in a mixed parallel series arrangement. Numerical values for component mean time to failure and mean time to repair parameters came from recommendations in the ACIM handbook [Ref. 2: p. 21].

The following sequence was used for model comparison:

1. Each of the three models was used to compute a recommended optimal inventory level for each system configuration given a specific budget and mean supply response time (MSRT) goal.
2. These inventory levels were input to the TIGER program individually and the resulting operational availability (A_o) of the steering system was estimated using a ship's mission timeline in the TIGER model for each configuration.
3. Model effectiveness for ACIM, LEO and SEASCAPE was compared in each of three scenarios. A_o was used as the measure of effectiveness for logistic support when comparing the three models because A_o is the established indicator of material readiness of a system.
    a. The first scenario compared model effectiveness using a fixed budget.
    b. The second scenario examined the three models at a range of different budgets.
    c. In the third scenario mean supply response time (MSRT) was varied over a range of values and model effectiveness was again compared.

TIGER is a simulation computer program which is capable of simulating systems under varying operating conditions for specified time periods. Some limitations with using TIGER to compare inventory models exist. These model limitations, which will be discussed in more detail in Chapter II, include the following assumptions:

1. Exponential or gamma failure times.
2. Exponential repair times.
3. Independence of equipment and component failures.

C. MAJOR TOPICS

Chapter II discusses the TIGER simulation model which was used to compare inventory level effectiveness. TIGER is a flexible model that allows for sensitivity analysis

by modifying part parameters and system configuration. TIGER was used to estimate the resulting system operational availability (A_o). Chapter III outlines the LEO model, an inventory model presently under consideration to compute spare part allowances for naval weapon systems at FMSO and NAVSEA. Chapter IV explains the SEASCAPE model presently used to compute repair part allowances for the AEGIS class cruisers. Chapter V describes the structure and mathematics of the ACIM model. Chapter VI presents test results for the models studied and Chapter VII summarizes the thesis and presents the conclusions and recommendations derived from the analysis. Also, included are recommendations for further research in the area of inventory model comparison.

II. NAVSEA TIGER SIMULATION MODEL

A. INTRODUCTION

TIGER is a computer program written in ANSI 77 FORTRAN which uses Monte Carlo simulation techniques to examine the reliability, maintainability and availability (RM&A) characteristics of complex systems of repairable equipment. TIGER can simulate the behavior of complex systems under varying conditions for a specified period of simulated time.

The current version of TIGER is version 8.20 dated April, 1987. The program was run on the Naval Postgraduate School's IBM 3033 mainframe computer from November 1987 through March 1988 for the purpose of comparing availability based inventory model used in this thesis.

TIGER can be used to analyze complex systems with numerous operating constraints. Such cases are frequently too difficult to model with closed form mathematical expressions. TIGER is a large and versatile simulation model, created especially for the study of the RM&A characteristics of Navy systems.

B. MAIN FEATURES OF TIGER

1. Input parameters

Equipment items are the basic entities of TIGER simulation. The user names the different types of mission-essential equipment in the system, then assigns their failure and repair properties.

The system description is used to instruct the program how to assess system state as a function of equipment state. The formats for TIGER input provide a practical way to translate reliability block diagrams into computer-readable information. The user supplies the necessary logic to TIGER in the form of system descriptions. One system description is required for each different kind of phase appearing in the timeline. TIGER system descriptions employ a hierarchical group structure, directly related to the reliability block diagram.

In TIGER the user may use either gamma or exponential failure distributions. To select an exponential distribution a shape parameter equal to one is specified. To obtain a gamma failure distribution an integer value greater than one is used as an input value for the shape parameter.

Normally, all repairs are performed by a general shop whose capacity is considered unlimited. However, the user may limit the capacity of the general shop or vary the number or shops up to twenty. If the user limits shop capacity, this constraint affects active repair. When an equipment item fails it must first wait until the necessary spare parts are on hand, then go to the end of the repair queue for its assigned shop. The user may exert queue discipline by assigning repair priorities to parts. These values range from zero to nine with zero as the highest priority.

In this study, all parts were assigned priority zero and shop capacity was unlimited.

2. Simulation

TIGER is an event driven, stochastic simulator. Random numbers drawn from an internal subroutine are used to generate equipment failure item and repair times. These random numbers are generated from an exponential distribution for repair times and either exponential or gamma distributions for failure times. Based on the system configuration, the system up and down times are determined. Then based on these up and down times, system measures of performance are calculated. The simulation is repeated a specified number of times depending on the precision desired. In general, the results are averaged to obtain values needed to compute mathematical quantities.

In TIGER, all internally generated events are equipment events of the following types:

- Failure of an equipment.
- Arrival of a spare part for a waiting equipment.
- Release of a repair channel for an equipment awaiting repair.
- Repair of an equipment.

"The mission begins with all equipment items in good condition and all stocks are up to allowance. The first failure of every equipment is forecast and placed on the schedule. The program then simulates the mission timeline, phase by phase. The processing of a phase sequence includes the following steps:

1. Process all expendable equipment in the phase.
2. Assess system state according to the system description for this phase.
3. Find the next equipment event.
4. Collect equipment statistics.
5. Assess system state according to the system description.
6. Collect system and subsystem statistics.

7. Execute any applicable operating rules (i.e. is repair of particular equipment allowed during this phase.)

8. Schedule another event for the same equipment considering the equipment MTBF, MTTR, and accessibility of spares.

9. Return to step 3 (Find the next equipment event).

Concurrently, TIGER observes the timeline. At the end of each phase sequence the program re-assesses system state, checks for operating rules, turns equipment items on or off if they are entering or leaving the system, and then simulates the next phase sequence in the timeline."

[Ref. 3: p. 23].

3. Exponential or gamma failure distribution

The term 'stochastic' implies that some of the inputs are expressed as statistically distributed values. A random failure time is generated using the input failure distribution and a random repair time is generated using the exponential distribution. TIGER allows a choice of exponential or gamma failure time distributions. The mission is simulated many times, the trial outcomes are statistically processed, and the results are reported in terms of means and standard deviations of the trial outcomes.

Previous versions of TIGER assumed that failure and repair were exponentially distributed. The exponential distribution uses MTBF or MTTR as its sole parameter. However, the exponential distribution ignores equipment wearout and burn in.

"For situations where the user knows two statistical parameters (MTBF and shape factor), TIGER version 8.20 offers the gamma distribution for failure times. Gamma MTBF and shape factor are calculated from the mean and standard deviation of actual equipment failure data. The gamma failure is preferred because it has a smaller variance than the exponential and requires fewer mission trials to produce a given precision of results. In TIGER, equipment repair times are always assumed to be exponentially distributed with known mean time to repair (MTTR)." [Ref. 3: p. 44].

C. TIGER LIMITATIONS

Limitations to the use of TIGER include the following:

1. Exponential or gamma failure time distribution.
2. Exponential repair time distribution.
3. Independence of equipment failures.

All system components failure distributions are assumed to be independent of each other. That is, a failure of one component will not cause the failure of another

component. Independence of equipment failures does not reflect actual naval system performance.

Under some scenarios and for many types of equipment the exponential failure rate assumptions may be valid, but certainly many types of equipment exhibit burn in and wearout. Also, not all repair times are exponentially distributed. In reliability theory repair time is usually lognormally distributed.

D. TIGER OUTPUT

The statistics calculated by TIGER are system reliability, readiness and average availability. Average availability, $\overline{A}_{om}$, is defined as the probability that the system is up and capable of satisfactory operation at any random point in the timeline, averaged over mission time. TIGER calculates average availability as:

$$\overline{A}_{om} = \frac{\text{Total system uptime in all trials}}{\text{Total simulation time}}$$

This is equivalent to:

$$A_o = \frac{MTBF}{MTBF + MTTR + MSRT}$$

where,

MTBF = Mean Time Between Failure

MTTR = Mean Time To Repair

MSRT = Mean Supply Response Time

It should be noted that time devoted to preventive maintenance is not included in this definition of A_o .

Another set of statistics used in this thesis is the critical equipments summary produced by TIGER. This is an optional printout that points out parts that are "worst offenders." Parts that caused the system to go down or parts that failed while the system was already down are listed in this output. Parts that are large contributors to system downtime can be easily identified through the critical equipments summary. Inventory models can then be analyzed to isolate possible weaknesses.

Explanations of the other available TIGER statistics such as equipment performance statistics, equipment failure by equipment number or type, summary of spares used,

and other statistics which describe system performance are found in the TIGER manual [Ref. 3: p. 10-1 thru 10-19].

III. LAGRANGIAN EQUIPMENT OPTIMIZATION MODEL (LEO)

A. MODEL DESCRIPTION

The Lagrangian Equipment Optimization Model (LEO) version 2.0 was developed by Advanced Technology as a tool to implement the availability centered inventory rule (ACIR) established by the Chief of Naval Operations (CNO). By this rule, program managers may compute and procure a spares inventory which achieves a specified A_o with the minimum total investment in spares. ACIR spares equipments or systems according to the effect upon overall operational availability, as opposed to the traditional philosophy which determines the [illegible]vance quantities based upon demand (FLSIP).

LEO is an analytic, spare-to-a[illegible]lability model that selects spares to optimize either mission-average or steady-state system availability subject to as many as three resource constraints. A steady state system with cost as the only constraint was used in this thesis. The analytic methodology used in LEO 2.0 is a modified version of Lagrange optimization techniques. From input lists of system equipments, operating characteristics, and candidate spare parts, LEO selects spares that maximize system availability within the constraints.

B. LEO METHODOLOGY

The analytic methodology used in LEO is a version of Lagrange optimization techniques developed expressly for LEO. Availabilities in LEO 2.0 are based upon the time dependent availability (A_t) for each candidate equipment. The formula, derived for use in the LEO model, is expressed as:

$$A(t) = e^{\frac{-t}{\mu_o}} + \sum_{i=1}^{\infty} \left\{ e^{\frac{-t}{(\tau_i + \mu_i)}} - e^{\frac{-t}{\tau_i}} \right\} \tag{3.1}$$

where,

t = Time since start of mission

μ_o = Mean "up" time between the start of the mission and the first failure

μ_i = Mean "up" time between the i^{th} failure and the i^{th} + 1 failure

τ_i = Mean time between the start of mission and the i^{th} failure

Equipment availabilities are combined to provide system availability based upon standard series and parallel considerations. The steady state availability was obtained as follows:

$$\text{Steady state availability} = \lim_{T\to\infty} \frac{1}{T}\int_0^T A(t)dt = \lim_{T\to\infty} \overline{A}_T \qquad (3.1)$$

[Ref. 4: p. A-1].

The LEO documentation does not explain the objective function in detail. However, due to the nature of the LEO output it is believed that the form of the LEO optimization problem formulation is as follows:

Maximize $\lim_{T\to\infty} \overline{A}_T$

subject to:

$$\sum_{j=1}^{N} c_j x_j \leq b$$

where,

j = Component j
N = Total number of components in the system
c_j = Cost of component j
x_j = Number of component j stocked onboard
b = Budget constraint value

The above formulation states that the total cost of all components stocked onboard must be less than or equal to the allotted budget. The x_j's are the decision variables in this formulation.

C. LEO LIMITATIONS

The LEO model contains the same assumptions that the TIGER model has. The following is a list of LEO model assumptions:

1. Exponential failure distribution.
2. Independent component failures.
3. Exponential repair times.

D. LEO INPUT

To run LEO, an input data set must be created. The standard medium is a disk file containing eighty column card images. LEO will accept either fixed format or free format data. The LEO 2.0 input deck consists of four sections: data specifications, mission design parameters, equipment parameters and composite function parameters.

E. LEO OUTPUT

LEO 2.0 output consists of four sections: resources and achieved availability; system equipment configuration and availability achieved; sparing levels and resource expenditures; and the input data list.

1. Resources and achieved availability

This section contains the LEO 2.0 design parameters: the mission availability goal, the mission length in days, and the resource constraints and their units. The next statistics shown in this section are the inherent availability and minimum spares availability. The inherent availability is the maximum availability which could be obtained by the system given its present configuration and attributes. The inherent availability is the availability that would result from infinite sparing levels. Similarly, the minimum spares availability is the availability achieved if no spare parts are assigned to the system other than those which are input as minimum requirements. Inherent availability and minimum spares availability are the maximum and minimum bounds of the system availability. Finally, the optimal achieved availability and the resource expenditures for the spare parts required to obtain that achieved availability are shown in this section. It is important to note that the achieved availability is the greatest availability that can be obtained within the constraints. The achieved availability is rounded to 3 decimal digits when printed. If the achieved availability is greater than 0.9995, then 0.999 with a "greater than" symbol is printed.

2. System equipment configuration and availability achieved

This section contains the notional reliability block diagram (RBD) for the system spared and the equipment's availability resulting from LEO 2.0 optimal sparing.

3. **Sparing levels and resource expenditures**

The sparing levels and resource expenditures section displays the optimal sparing levels and their parameters developed by LEO 2.0. Also displayed in this section are the total system availability, and the amount of resources 1, 2, and 3 (cost, weight, volume) expended to obtain this system availability by the alternative sparing policy (such as FLSIP) for use in comparison analysis.

4. **Input data list**

This section displays the input data used for the LEO run which allows a verification of the input values to assure the user that the correct input values were entered in the correct data fields. This section is divided into four sub-sections: design parameters, equipment parameters, composite function parameters, and spares procurement parameters.

Design parameters are those parameters used by LEO to develop the spares suite that optimizes availability. They include the mission name; the resource 1, 2, and 3 constraints and their units; and the availability goal.

Equipment parameters are those parameters used to describe the system's equipment from input records. The equipment is listed in equipment indenture level and the following information is displayed: the indenture level, equipment specifications, number of equipments installed and required, the mean time between failures (MTBF), the equipments spare's resource expenditure, the mean time to repair (MTTR), and the mean supply response time (MSRT).

The composite function parameters section contains those function codes used to describe the system. The information included in this section includes the function code, the number of subfunctions required to fulfill the function, and the stand-alone/redundancy indicator for the function. The function code allows the user to name each equipment in the system so the total system can be described using these equipment names or function codes. The stand-alone/redundancy indicator allows the user to indicate whether the equipment is parallel or series configured.

The spares procurement parameters section identifies the supply support parameters. The following information is given for each spare equipment:

1. Index number
2. Equipment specification
3. Equipment name
4. Other supply related information.

IV. THE SEASCAPE MODEL

A. MODEL DESCRIPTION

Spares Economically and Automatically Selected by Criteria Applied for Performance Effectiveness (SEASCAPE) was developed for the AEGIS weapon system. The prime objective in the development of the SEASCAPE methodology was "to provide a quantitative decision aid for establishing prioritized ordering policies that are economically supportive of high levels of system readiness (operational availability)." [Ref. 5: p. 33].

A key factor in the development of SEASCAPE was the unique design characteristics of the AEGIS weapon system. AEGIS's maximum performance is based on a set of key design parameters including fire power and target detection range. A required performance (called level I performance) was defined to establish the boundary between system up and down conditions, i.e. the system may still be up but operating at a reduced capability. The region between maximum and required performance is called the performance margin. The AEGIS system design takes advantage of this performance margin by providing for performance levels within the margin. The result is a fault tolerant design for which very few single component failures take the entire weapon system down. This is accomplished through design techniques such as redundancy, load sharing, and channelization. Fault tolerant design is a *major* characteristic leading to the high level of inherent availability achieved by the AEGIS weapon system. Significant sparing advantages also occur from this design approach. Those components and parts incorporated in the fault tolerant design can serve as the equivalent of built-in spares in the overall sparing strategy. The SEASCAPE methodology takes advantage of this capability to give full consideration to these built-in spare equivalents.

B. SEASCAPE LIMITATIONS

The SEASCAPE model contains the same assumptions that the TIGER and LEO models have. The following is a list of SEASCAPE model assumptions:

1. Exponential failure distribution.
2. Independent component failures.
3. Exponential repair times.

C. SEASCAPE INPUT

The SEASCAPE data input does not conform to the normal eighty column line used on most computer systems. SEASCAPE data input records are two hundred columns wide. Included on the data input records are the following types of information:

- System configuration characteristics - redundancy, channelization, and series.
- Supply system characteristics - logistic delay times and ordering priority level of each repair part.
- Repair part characteristics - failure rates, repair times, and cost.

D. SEASCAPE OUTPUT

Before examining the output reports produced by SEASCAPE the following output parameters require definition:

Logistic down event occurs when the equipment is inoperative due to the lack of appropriate onboard repair parts.

Logistic availability (A_L). is the proportion of time that an equipment or system is expected to perform as required or if down, can be repaired using onboard repair parts.

$$A_L = \frac{MTBLDE}{MTBLDE + MLLDE}$$

where

MTBLDE is the mean time between logistic down events

MLLDE is the mean length of logistic down events.

Mean time between logistic down events (MTBLDE). MTBLDE is the mean time to pass from an "up" state to a "down" state which cannot be restored with onboard repair parts.

Mean length of logistic down events (MLLDE). MLLDE is the mean down time measured from the time a replenishment order is initiated until the replenishment part necessary to restore performance is received from off ship. MLLDE is similar to the mean supply response time (MSRT) used in TIGER, LEO and ACIM.

Configuration integrity factor (CIF). The AEGIS weapon system's fault tolerant design provides the equivalent of spares within the system. The logistics availability A_L parameter treats all fault tolerant features equally. The CIF parameter is introduced to resolve the dilemma of all fault tolerant features being treated equally.

Output reports

With these terms explained we will examine the output reports produced by SEASCAPE. There are a variety of output options associated with the SEASCAPE model. The most comprehensive output available from SEASCAPE provides the following reports:

1. Model input factors
2. Equipment logical set characteristics for SEASCAPE provisioning analysis
3. Model item input data
4. Spares summary report
5. Spares summary totals report
6. Logical set summary

The first three reports are provided to allow the user to verify input parameters. The remaining three reports are described below.

The spares summary report lists each item by number and name. It gives a recommended stock level for each line item and computes the cost to stock the item to this level.

The spares summary totals report gives the total cost of stockage for all items and gives a breakdown of cost by equipment type. This report also lists the percentage of high priority requests, mean time to restore (MTTR), logistic (MLLDE) and mean time between failures (MTBF), logistic (MTBLDE), configuration integrity factor (CIF) and sustainability for x number of days.

The logical set summary displays the equipment divided into groups or logical sets and lists the number of components in each logical set and the cost to stock spares for each logical set.

V. ACIM MODEL

A. MODEL DESCRIPTION

The Naval Sea Systems Command's Availability Inventory Model (ACIM) was developed after the Chief of Naval Operations directed that "a sophisticated availability-based sparing technique be developed and applied on a selected basis for equipments which require a level of readiness above that which standard polices can provide." [Ref. 2: p. 23]. ACIM is a standard availability centered model which is used by program managers in determining consumer level stockage quantities for selected equipments. ACIM develops repair part allowances to achieve a specified A_o at the minimum possible inventory cost.

The ACIM model was developed by Consolidated Analysis Centers, Incorporated (CACI). This chapter will describe the ACIM model as it applies to inventory level determination in this thesis.

ACIM is a very flexible model. It can solve either of the following problems for multi-echelon or single echelon supply systems:

1. Select a minimum cost inventory of spares for a system so that the system will achieve a given availability target.
2. For a given budget, select a collection of spares that will maximize availability.

The ACIM definition of availability is the same as that used in the TIGER simulation model:

$$A_o = \frac{\text{UPTIME}}{\text{UPTIME} + \text{DOWNTIME}}$$

ACIM replaces uptime by MTBF and downtime by mean time to repair (MTTR) plus mean supply response time (MSRT). So A_o can now be expressed as:

$$A_o = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR} + \text{MSRT}}$$

Time devoted to preventive maintenance is not included in this definition of A_o .

The MTBF and MTTR parameters are inputs to the ACIM model. The MSRT parameter is dependent upon stockage levels. ACIM uses this dependency to achieve a

target value for A_o. In reality ACIM attempts to minimize MSRT in order to maximize A_o

B. MODEL LIMITATIONS

ACIM is a steady state model. This means that the model operates on the assumption that all flows through the repair and supply pipelines are stabilized. The inventory system is assumed to be operating at a constant rate over a long period of time. Therefore, the model cannot be used to investigate surges in demand periods.

ACIM has a few computational approximations that should be noted. The first concerns ACIM's approximation of availability. ACIM assumes that no other system failures can occur after the first system failure occurs. In an actual ship system, a single part failure may only degrade the system performance rather than cause the entire system to shut down. The system may continue to operate and parts continue to fail after the first part fails. In addition, the process of minimizing MSRT does not always yield the same inventory levels as maximizing availability. For some systems the results are similar, but for other systems there may be large differences. A possible reason these differences occur is because the minimizing MSRT process may choose a part with a low MSRT before a part with a low MTBF, while a process maximizing A_o may choose a part with a low MTBF instead of a part with a low MSRT.

When using the ACIM model to match a target budget (or availability), the iterative process only approximates the target goal. The ACIM algorithm will always exceed the target because it adds an item to the inventory until the target is reached.

The ACIM model requires a significant amount of work to create the input data. The exact indenture level of parts, part parameters, and maintenance facility information are required. Nevertheless, ACIM appears to be a useful tool and can be expanded to encompass many repair facilities at different levels, handling inventory problems of very complex systems.

The underlying model assumptions of ACIM are as follows:

1. Included parts are organized in terms of an equipment with a top to bottom breakdown. If there are multiple numbers of a particular part in an equipment it is represented only once. However, if there are multiple numbers of a particular part in different locations in the system, each appearance is treated as a unique item in the operation of the model.
2. The distribution of the number of demands upon off ship supply are stationary and are Poisson distributed.
3. All shipboard stockage locations use a continuous review ordering policy.

4. Mean times to repair (MTTR) are defined as constants which include all equipment repair related downtimes that are not supply related.
5. Component failures are independent.
6. Once a part fails in the system, no further failures can occur and the system cannot operate, unless it has built-in redundancy.

C. INVENTORY DETERMINATION

1. ACIM Mathematical Description

The structure of the availability centered inventory rule (ACIR) and its solution procedures are defined by a set of interrelated equations. The following mathematical description of the model is taken from the ACIM Handbook [Ref. 2: p. A-2 - A-9].

The model is defined recursively by considering an arbitrary item in the equipment and an arbitrary facility such as a ship. The structure of the model is given by the following set of definitions and equations:

A. Let i be an arbitrary item in equipment e (which may be e itself). Let $u=0$ represent an arbitrary facility in the support system.

Once a part in the system has failed the mean time for the failed part to return to operation is given by the following equation:

B. $M_{iu} = D_{iu} + T_{iu}$

where:

M_{iu} = mean time to return a failed unit of item i at location u to a serviceable condition.

D_{iu} = expected time delay per demand upon inventory for item i at location u.

T_{iu} = mean time to repair item i at user location u (for equipment repair).

In equation B, the factor T_{iu} represents the marginal mean time to repair item i through replacement from stock or repair of failed subordinate parts. Included are all repair related functions such as documentation, fault isolation, removal and replacement, and system checkout. These factors are assumed to be given as constants.

The expected time delay per demand upon inventory for item i at location u is given in equation C.

C. $$D_{iu} = \frac{1}{\lambda_{iu}} \sum_{x \geq S_{iu}} (x - S_{iu}) p(x; \lambda_{iu} T_{iu}) \qquad (u = 0,1,2,...,U)$$

where:

S_{iu} = stock level of item i at location u.

λ_{iu} = expected number of demands upon inventory for item i at location u.

$p(x; \lambda_{iu} T_{iu})$ = probability of x units of stock reduction for item i at location u.

In equation C, the summation term gives the expected number of backorders for a stock of S_{iu} during the repair cycle of length T This is equivalent to the expected length of time the stock is in a backorder status. Dividing the expected number of backorders for a stock of S_{iu} by the expected number of demands per time unit gives the expected delay in satisfying a demand. The time unit for all equations in ACIM is days. Values for λ_{iu} are assumed to be given as input data in ACIM.

The mean time to repair item i at user location u is given in equation D below.

D. $$T_{iu} = \gamma_{iu}(L_{iu} + L'_{iu}) + (1 - \gamma_{iu})(R_{iu} + R'_{iu})$$

where:

γ_{iu} = probability that a demand for item i upon inventory at location u results in a loss of the repairable part (discard or sent elsewhere for repair) which must be replaced through resupply from an intermediate level supply source.

L_{iu} = average resupply lead time assuming stock is available at the intermediate level supply source.

L'_{iu} = additional resupply lead time due to expected shortages at the intermediate level supply source.

R_{iu} = average shop repair cycle time assuming the spare parts needed to repair item i are available.

R'_{iu} = additional shop repair cycle time due to expected shortages of one or more of the spare parts needed to repair item i.

In equation D, the factors γ_{iu} are assumed given by input data. The factors L_{iu} and R_{iu} are assumed to be given as constants for each location. The first term (involving resupply lead times) represents losses from stock due to scrap or units sent to higher level repair facilities. The second term represents losses due to amounts cycling through local repair.

E. $L'_{iu} = D_{iu}$ $(u = 1,2,...,U)$

$L'_{i0} = D_{iv}$ where v is the resupply source for location $u = 0$.

$L'_{i0} = 0$ if location 0 has no resupply source.

Equation E states that the additional delay in obtaining resupply is equal to the expected delay per demand upon stocks at the resupply source.

F. $$R'_{iu} = \frac{\sum_{j \in I} \lambda_{ju} M_{ju}}{\sum_{j \in I} \lambda_{ju}}$$

where j identifies items within i at the next lower indenture level. Note that $R'_{iu} = 0$ if i has no subordinate parts.

Equation F states that the additional delay in repairing an assembly is equal to the weighted average of expected delays per demand upon stocks at the next lower indenture level.

G. $$A_{eu} = \frac{1}{(1 + \lambda_{eu} M_{eu})}$$

where:

A_{eu} = fraction of time equipment e is available for use at location u (defined only for locations u which operate the equipment).

λ_{eu} = expected number of demands upon inventory for equipment e at location

u .

Equation G gives the operational availability of the equipment in terms of factors defined by previous equations. With proper interpretation of terms, this definition can be translated into other expressions more common for A_o.

The above definition of the model is recursive on the "items" within the parts hierarchy and their "locations" within the support system hierarchy. If stock levels are given for all items at all locations, a recursive procedure using the equations may be applied to determine corresponding operational availabilities of the equipment at all user locations. The recursion starts with items at the bottom of the parts hierarchy. For such items and locations, additional resupply and repair times (equation E and F) are zero, and expected delays can be calculated directly using equations C and D. These delays can be used in equations E and F to calculate additional resupply and repair times. Expected delays for these items and locations can then be determined by equations C and D.

2. Objective Function

The overall objective of the ACIM model is to determine inventory levels for all items and all stockage facilities such that the expected operational availability of the equipment is maximized for a given inventory budget or, conversely, to find inventory levels which achieve a given operational availability at least cost. This objective can be explicitly stated as follows:

Find values for S_{kv} for all items $k \in e$ and locations v in the support system which minimize $D = D_{eu}$ for all user locations u subject to:

$$\sum_{k,v} c_k S_{kv} = B$$

where:

c_k = unit cost of item k

B = given budget for spares procurement

Equations B and G show that minimizing D_{eu} is equivalent to maximizing A_{eu}, the operational availability of equipment e at user location u .

3. Solution Procedure

The ACIM optimal solution to the problem defined above is found by a recursive procedure based upon equations B through G. First, however, a subproblem is defined and a solution procedure is given for the subproblem. A recursive application of the subproblem is then used to solve the original problem. This subproblem solution is described in the ACIM manual [Ref. 2: p. 23].

D. ACIM INPUT

The ACIM program is made up of three subprograms that operate in sequence. The first program (preprocessor) calculates stockage levels according to designated comparison policies. The second (main) program of the model calculates levels according to ACIM. Stockage levels calculated by the first and second programs are passed to the third program (postprocessor) which produces three output reports: a cost-effectiveness report, a levels by items summary, and a statistical summary report.

Data is input using record formats of which there are three types: options and default values, site data, and item data.

E. ACIM OUTPUT

ACIM output consists of the following three standard reports:

1. Cost-effectiveness report

This report displays data corresponding to units of stock added to inventory by ACIM's optimal availability algorithm. Every n^{th} unit added to stock, or units which cause the achieved availability or investment to reach specified incremental values, will be printed.

2. Levels by item summary report

The levels by item summary report is designed to show the stock levels calculated for each item by the availability centered and comparison policies.

3. Statistical summary report

This report is designed to show overall results of the model in terms of stockage cost and performance.

This ends the discussion of the models compared in this study. The next chapter will discuss test results obtained from inputting inventory levels into the TIGER program.

VI. TEST RESULTS

A. INTRODUCTION

This chapter presents TIGER simulation results which evaluate the performance of the ACIM, LEO, and SEASCAPE provisioning models with regard to achieved availability. This evaluation was conducted using a short operational scenario and two different configurations of a ship's steering system. One configuration of the ship's steering system places all components of the system in series. The other configuration contains a mix of series and parallel connections between the components.

Each of the provisioning models was used to produce shipboard allowance quantities under a variety of conditions. These conditions can be summarized in the following three categories:

1. **Fixed Budget.** Achieved availability is compared for the three inventory models using a fixed budget constraint for each model.
2. **Variable Budget.** Availability is compared while varying the budget over a range of values.
3. **Variable Mean Supply Response Time (MSRT).** Availability for each of the three inventory models is analyzed and compared with a variable MSRT parameter.

For each of the three scenarios it was assumed that spares decisions would be made for identical ship steering systems. Availability is computed for a period of sixteen days (384 hours) with each ship steering system underway for 10 days (240 hours) of the 16 days.

Each simulation trial using TIGER was divided into the following three phases. A cruise phase (7.5 days, 204 hours), an operations phase (1.5 days, 36 hours), and an upkeep phase (6 days, 144 hours). The cruise phase is one in which the ship is traveling to or from the operating area or is traveling at night. The operations phase is a phase in which the ship is actually engaged in some type of fleet operation such as an ASW exercise or a missile firing exercise. The upkeep phase is one in which the ship is inport for two weekends for repairs and reprovisioning. This schedule is indicative of a two week period in which a ship is underway for two days inport for 3 days, underway for 8 days, and inport for 3 more days. Each test run using TIGER consisted of 750 iterations to obtain three digit precision.

The ship steering system was composed of eight different part types with a total of fourteen individual parts. Table 1 on page 25 lists the basic input data for each part type.

Table 1. PART PARAMETERS

Part Type	Part Name	Unit Cost	MTBF (hrs)	No. in Syst
1	Bridge Control	$34940	257	2
2	Electric Control	$13670	352	2
3	Local Control	$10550	658	1
4	Motor Controller	$21930	667	1
5	Electric Motor	$37500	272	3
6	Hydraulic Pump #1	$3520	699	1
7	Hydraulic Motor	$38850	196	1
8	Hydraulic Pump #2	$5060	1124	3

Initially, the system was in a configuration in which all fourteen parts were connected in series. The system was also arranged in a mixed of series and parallel connections between the components as depicted in Figure 1. This mixed parallel/series system will be referred to as the "parallel" system for remainder of this study.

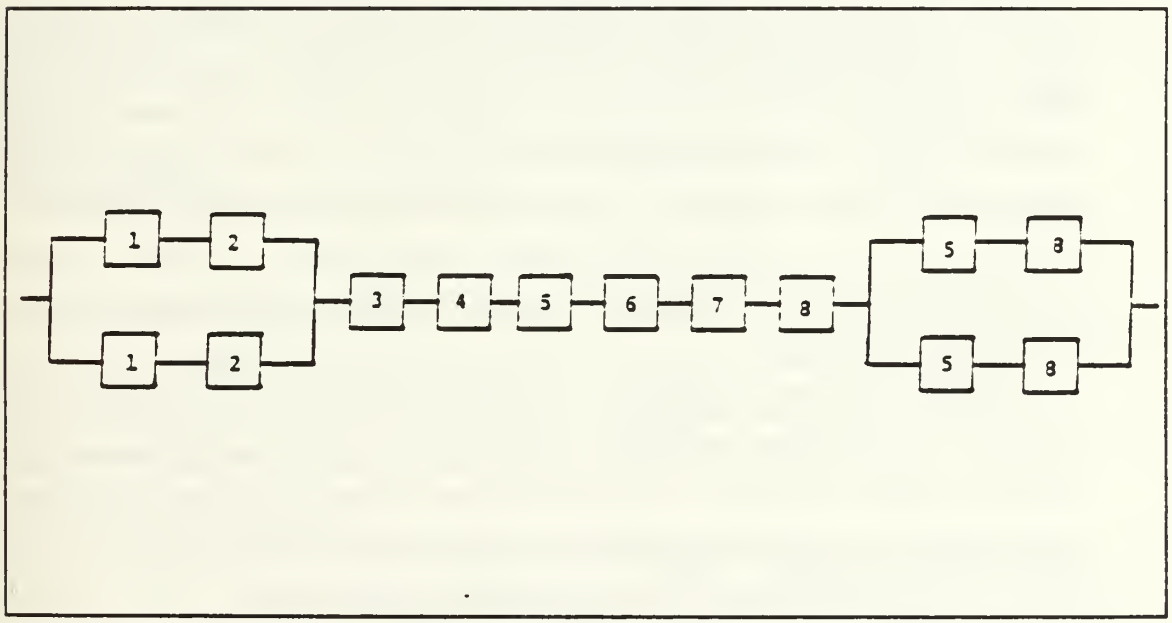

Figure 1. Mixed parallel/series system configuration

B. FIXED BUDGET ANALYSIS

The object of this portion of the study was to examine the effectiveness of the individual inventory models when all three models were constrained to the same budget level. The inventory levels computed by each of the three inventory models were the input variables to the TIGER program. TIGER generated system availability values for each of the three models. These system availability values were compared to determine which of the three inventory models yielded the highest system availability value for the given scenario.

Extra effort was made to ensure that the three models were compared on an equal basis. This turned out to be quite difficult because of the differences among the models. The ACIM and SEASCAPE models are very similar so the parameters were matched for these two models first. The LEO model parameters were then matched to the ACIM/SEASCAPE parameters.

A value of 17.5 days (420 hours) for MSRT was used in all three models because the ACIM model recommended this as a benchmark value. A mean time to repair (MTTR) of .083 days (2 hours) was used for all components in all three models and also in TIGER during the evaluation phase. All other parameters used are listed in Table 1 on page 25.

The next step was to generate inventory levels using each model with a fixed budget. This was accomplished by first using the SEASCAPE model to arrive at a benchmark budget level. The SEASCAPE model was used to establish the benchmark budget because SEASCAPE was the most difficult model to try to match a given budget level. Using the parameters discussed above, the total SEASCAPE inventory cost was $680,360. Next, the ACIM and LEO target budgets were set to a value equal to that of the SEASCAPE budget. The ACIM and LEO models arrived at budgets of $675,300 and $701,650 respectively.

The resulting inventory levels are summarized in Table 2 on page 27 and Table 3 on page 27. The resulting availability values for both system configurations are summarized in Table 4 on page 27. The effectiveness of both the ACIM and SEASCAPE models appears to be better than that of the LEO model. SEASCAPE seems to perform slightly better than ACIM in both the series and parallel systems.

The lower performance of the LEO model in comparison to the other two models can be explained by examining the inventory decisions made by the LEO model. First, the critical parts of the series system are found by examining the critical equipments list

Table 2. FIXED BUDGET MODEL SUMMARY (SERIES CONFIGURATION)

		Stock Level by Part Type							
Model	Budget	1	2	3	4	5	6	7	8
ACIM	$675,300	5	5	2	2	6	3	3	3
LEO	$701,650	5	8	3	2	6	4	2	5
SEASCAPE	$680,360	5	5	2	2	6	3	3	4

Table 3. FIXED BUDGET MODEL SUMMARY (PARALLEL)

		Stock Level by Part Type							
Model	Budget	1	2	3	4	5	6	7	8
ACIM	$675,300	5	5	2	2	6	3	3	3
LEO	$685,340	0	0	4	3	7	5	7	5
SEASCAPE	$670,450	4	4	3	3	4	4	5	4

Table 4. MODEL AVAILABILITY SUMMARY

Model	Avg Availability (Series)	Avg Availability (Parallel)
ACIM	.953	.960
LEO	.946	.809
SEASCAPE	.954	.961

in the TIGER output for the LEO model. The results of this list are summarized along with a part budget breakdown in Table 5 on page 28. The most obvious oversight is part type seven denoted with an asterisk. LEO spent only 11.07 percent of the total budget on part type seven yet this part accounted for 30.62 percent of the total unavailability of the system.

The LEO model failed to observe that despite being the most expensive part ($38,850) in the system, part type seven also had the lowest MTBF (196 hours) in the system. Therefore, part type seven needed to be stocked at a higher quantity to improve overall system availability.

The LEO model performed even worse in the parallel series configuration than in the series configuration. Although parts one and two were arranged in a parallel series configuration, at least one of each part was required ot be up for the system to be operational. Despite this fact, parts one and two were not stocked by the LEO model (see Table 3).

Table 5. CRITICAL EQUIPMENT ANALYSIS OF THE LEO MODEL

Part Type	Unit Cost	Nr Stocked	% of Total Budget	% of Syst Unavail
7	$38850	2	11.07%	30.62% *
5	$37500	6	32.07%	21.33%
2	$13670	8	15.59%	16.16%
1	$34940	5	24.90%	12.07%
4	$21930	2	6.25%	8.48%
3	$10550	3	4.50%	6.60%
8	$5060	5	3.61%	3.19%
6	$3520	4	2.01%	1.54%

C. VARIABLE BUDGET ANALYSIS

In the previous discussion each inventory model was studied at a single specified budget level. With constant changes to the Navy's budget a more important question concerns the performance of the models over a range of budget levels. With a decrease or increase in budget level, the decision maker may desire to adjust inventory levels accordingly.

The variable budget analysis was arranged as follows. Part parameters remained as shown in Table 1 on page 25 and mission time also remained constant at 384 hours.

A benchmark budget level of $680,360 was established, based on the SEASCAPE run described in section B. Alternate budget levels were varied from a low of $406,070 (60.83% of the benchmark) to a high of $802,200 (117.91% of the benchmark). The SEASCAPE model was run first, varying the allocation index (AI) value to arrive at an appropriate budget level. The allocation index (AI) value is the parameter in SEASCAPE that the user varies to select varying budget levels. Using the resulting SEASCAPE budget as a target budget, ACIM and LEO were then run. Inventory levels computed at each budget level for both the series and parallel systems are summarized in Tables 8 through 13 in Appendix A.

Using these inventory levels in the TIGER program, model effectiveness was analyzed using both the series and parallel systems. Table 6 on page 29 shows system average availability for all three models over the range of budgets. Budget percentages are also listed for each model. The average difference between SEASCAPE and the other two models was 1.22 percent with a maximum difference of 3.66 percent between budget levels.

The results of this test were that both the ACIM and SEASCAPE models again outperformed the LEO model. At lower budget levels the ACIM and SEASCAPE models were 14 to 15 percentage points higher than LEO while at increased budgets they were just 8 percentage points higher in the series system and 15 percentage points higher in the parallel system. SEASCAPE did better than ACIM at lower budget levels but they were equally effective at high budget levels for both system configurations.

Table 6. THREE MODEL PERFORMANCE FOR VARIABLE BUDGET

	Series			Parallel		
% Benchmark Budget	ACIM	LEO	SEASCAPE	ACIM	LEO	SEASCAPE
60-62%	.893	.751	.907	.918	.789	.929
77-79%	.934	.872	.934	.950	.807	.951
86-87%	.946	.881	.946	.955	.804	.956
92-94%	.948	.882	.949	.956	.804	.956
100-102%	.953	.946	.954	.960	.809	.961
103-105%	.952	.947	.952	.956	.810	.956
110-112%	.956	.949	.956	.965	.810	.965
115-117%	.956	.948	.956	.965	.810	.965

Figure 2 on page 30 and Figure 3 on page 31 show how the three inventory models compared graphically. As shown the ACIM and SEASCAPE models were more effective than the LEO model at all budget levels for both systems.

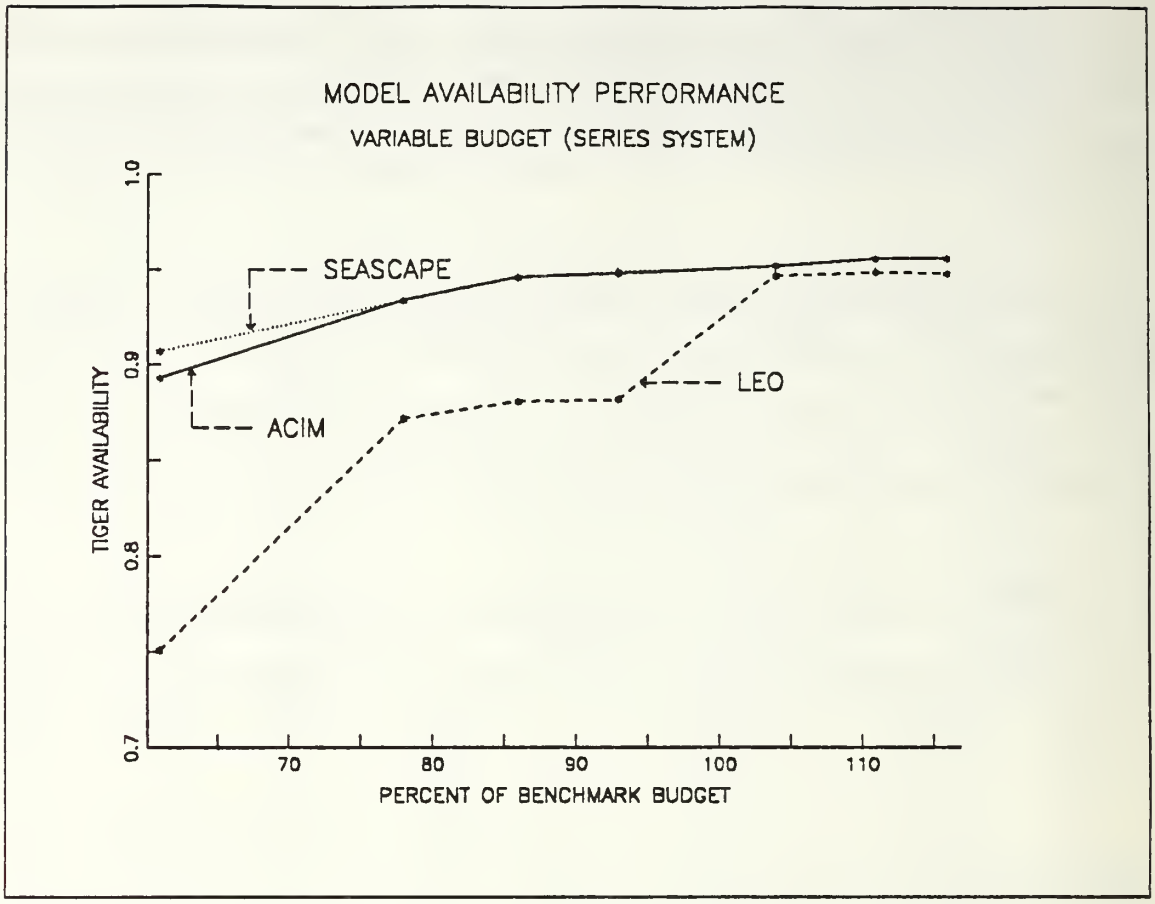

Figure 2. Three model performance for variable budget (series system)

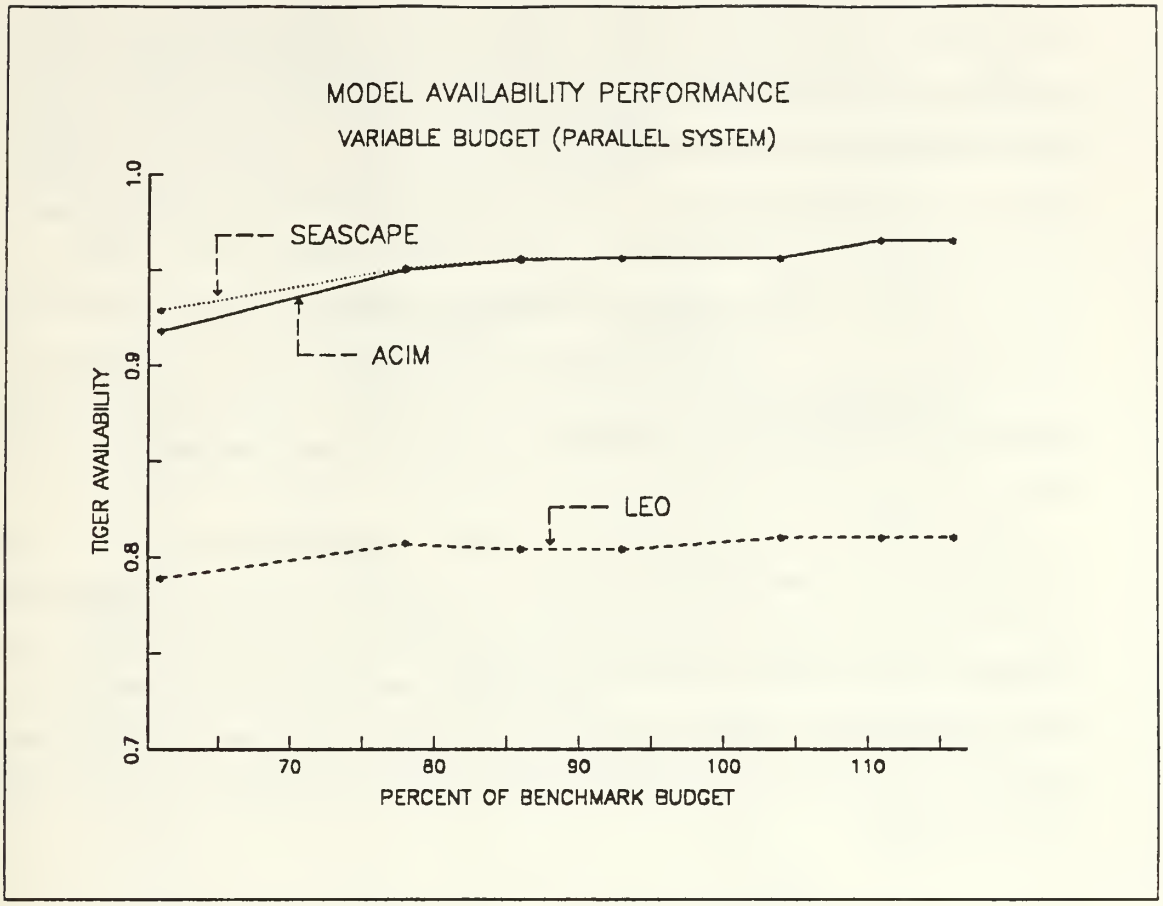

Figure 3. Three model performance for variable budget (parallel system)

D. VARIABLE MSRT ANALYSIS

For this portion of the study, the mean supply response time (MSRT) input to all three models was varied in order to investigate the effectiveness of a fixed budget inventory model over a range of MSRT values.

The methodology used for this test was as follows. The MSRT input parameter was varied from 12 days (288 hours) to 41 days (984 hours), while maintaining a constant target budget of $560,000. Inventory levels were computed for all three models and then run on the TIGER program. These inventory levels are presented in Tables 14 through 16 in Appendix B. TIGER parameters for repair and resupply times were matched to the corresponding MSRT's used in the models. System availability was analyzed for the series system only.

The ACIM statistical summary report, the LEO model output, and the SEASCAPE sustainability report include an achieved operational availability figure that theoretically could be achieved for a series system, given the inventory levels selected. These availability predictions or forecasts, along with availabilities calculated from TIGER simulations, are compared in Table 7. Several items should be noted regarding these results. All three models had projected availabilites which underestimated availability for all ranges of MSRT values. The A_o forecasted by the LEO and ACIM models greatly underestimated the A_o obtained from TIGER. While the A_o forecasted by the SEASCAPE model underestimated the A_o from TIGER. However, the difference between the forecasted A_o and the TIGER A_o was not as large as in the LEO and ACIM models.

Another noteworthy item was that as MSRT increased the LEO model continued to stock increasing numbers of part types 2, 3, 4, 6 and 8 while it allowed part types 1, 5 and 7 not to be stocked at all. This is very difficult to understand as this is a series configured system which requires all part types to be operational in order for the total system to operational. The ACIM and SEASCAPE models were not so extreme and continued to stock all items as MSRT increased, thus allowing for the series configuration of the system.

Table 7. THREE MODEL PERFORMANCE FOR VARIABLE MSRT

	ACIM		LEO		SEASCAPE	
MSRT	Forecast	TIGER	Forecast	TIGER	Forecast	TIGER
12	.792	.941	.473	.934	.807	.943
17.5	.608	.943	.139	.891	.811	.945
24	.365	.943	.010	.742	.823	.946
30	.224	.943	.001	.688	.792	.947
36	.146	.931	.000	.543	.792	.947
41	.113	.934	.000	.511	.724	.931

Figure 4 on page 33 shows the comparison between the models graphically. Note that the ACIM and SEASCAPE model availabilities do not decrease as MSRT increases. This may be caused by the differences in MTBF of the different part types spared at each MSRT level. For example, the SEASCAPE model has similar stock levels for 24 and 30 day MSRT. At these MSRT levels only part types 5 and 7 are stocked

differently. With a 24 day MSRT SEASCAPE stocks 1 unit of part type 4 and 5 units of part type 5, while with a 30 day MSRT 2 units of part type 4 and 4 units of part type 5 are stocked. The MTBF of part types 4 and 5 are 667 and 272 hours respectively, a difference of 395 hours. This is a substantial difference and appears to have made up for the increased MSRT for all parts in the system.

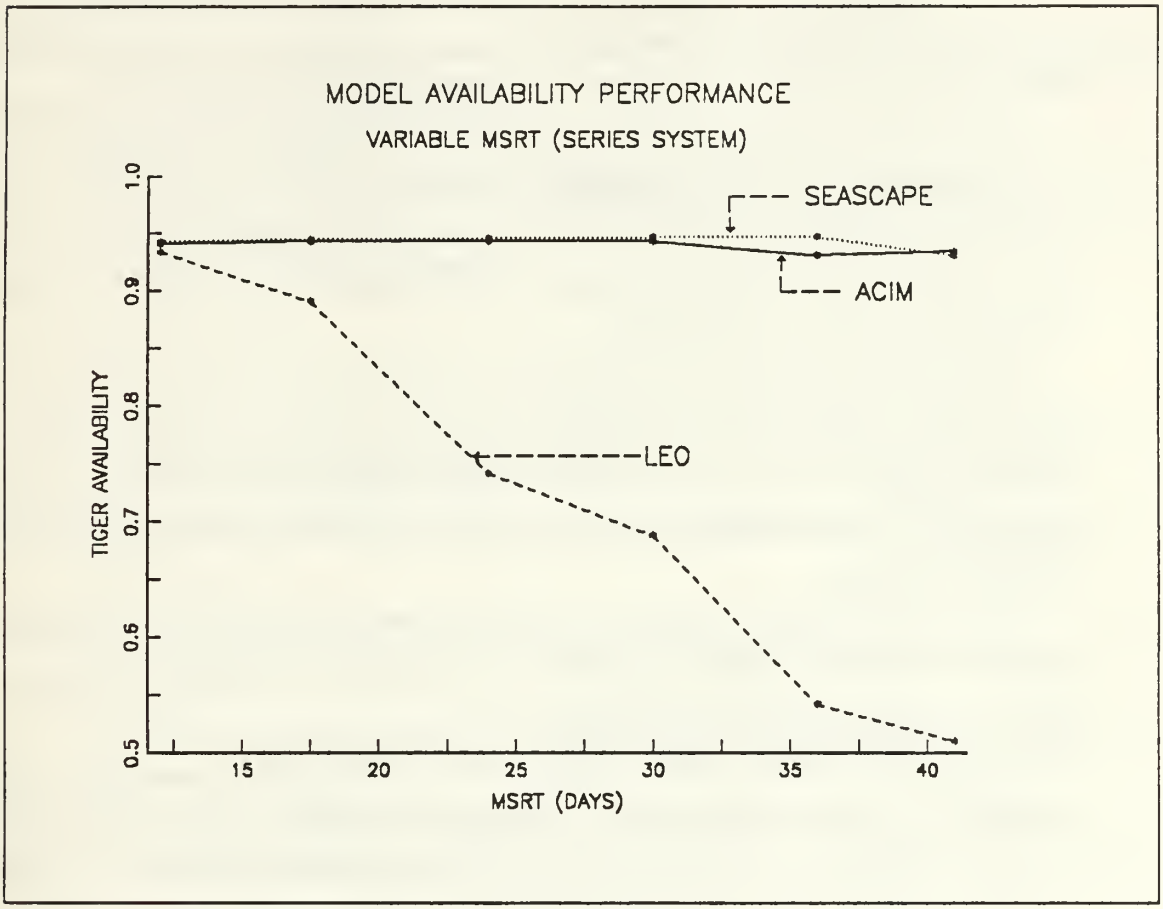

Figure 4. Three model performance for variable MSRT (series system)

VII. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSIONS

This study looked at three areas of inventory model effectiveness. The first area was a fixed budget analysis which showed some small differences in model effectiveness. Budget allocation for the LEO model was less efficient than the ACIM and SEASCAPE models for both of the hypothetical series and parallel configured ship steering systems.

Examination of the critical equipment summary of TIGER was helpful in finding inventory the weakness in LEO in this area. Despite the configuration of the steering system, the LEO model failed to stock part types one and two when both were required to be for the system to be operational.

The second area of study was a sensitivity analysis which examined the three models over a range of budget values. Budget levels were varied from 60% to 118% of a benchmark budget level. The result of the variable budget analysis showed that ACIM and SEASCAPE outperformed the LEO model at all budget levels for both the series and parallel systems.

SEASCAPE performed better than ACIM at lower budget levels but both models were equally effective at higher budget levels. This was due primarily to similarity in the stock levels recommended by each model.

The third area of study concentrated on the effects of varying mean supply response time (MSRT) on model effectiveness. Test results for LEO generally agreed expectations, that availability would decrease as MSRT was increased under a fixed budget, however, in SEASCAPE and ACIM availability remained nearly constant with an increase in MSRT. This indicated that SEASCAPE and ACIM inventory selection effectiveness were not affected by an increase in MSRT. The change in individual part stock levels as MSRT increased were noteworthy. With a fixed target budget, the models recommended different repair part inventory levels depending on the length of the MSRT.

Some of the advantages and disadvantages of each of the three inventory models are summarized below.

1. LEO Model

Advantages:

1. Easiest of the three models for conducting sensitivity analysis (variable budget and variable MSRT analysis).

2. Simplest input format to learn how to use and manipulate.
3. Simplest, most user friendly.
4. Handles up to three resource constraints. Typical such constraints would deal with cost, weight, and volume limitations.

Disadvantages:

1. Does not optimize budget allocation. LEO did not use all of its allotted budget although an increase in availability would have occurred had LEO used all of its allotted budget.
2. When simulating a parallel system configuration, all parts must be assigned to indenture level one. This is a confusing rule because a system may be made up of several indenture levels, but the rule must be followed so that the program will function properly.

2. ACIM Model

Advantages:

1. Powerful model which has the capability of computing multi-echelon inventories for multi-indentured systems.
2. Determines stock levels for either an availability target or a budget target.

Disadvantages:

1. Assumes that the failure of one part results in shutdown of all other parts in system.
2. The optimization process only approximates maximization of availability by minimizing MSRT.
3. Program is written in COBOL which is not as common a scientific programming language as is FORTRAN.

3. SEASCAPE Model

Advantages:

1. Takes advantage of the fault tolerant system design currently used in the AEGIS weapon system. This fault tolerant design allows components and parts incorporated into the fault tolerant design to serve as the equivalent of built-in spares in the overall sparing strategy.
2. Is equally effective in non-fault tolerant system designs as shown by this study.
3. The use of an allocation index (AI) allows the user to compute inventory levels for a wide range of budget levels.

Disadvantages:

1. The allocation index (AI) can also be a disadvantage because the process of varying the AI value to compute inventory levels for different budget levels requires substantial human and computer resources.

2. The data input format does not conform to the normal eighty column line used on most computer systems. SEASCAPE data input records are two hundred columns wide. A FORTRAN routine was written to deal with this problem in this thesis.

B. RECOMMENDATIONS

The TIGER model proved to be a capable evaluation tool, although it does have several limitations. The first limitation is common to all the inventory models used in this study: the assumption that all component failures are independent of each other. A model needs to be developed in which the user is able to allow for dependent failures of components. Most component failures have some effect on other components in the system, whether it requires the technician to turn the equipment off to repair it and then turn the equipment on again or it causes an unstable state such as a power surge to occur. Both of these events could cause additional component failures. Unfortunately, these models have no way to reflect this component failure dependency. Future research should include an effort to modify the TIGER simulation to included the representation of failure dependencies.

Another limitation of TIGER is that repair times are exponentially distributed. In reliability theory repair times often have a lognormal distribution. Adding the ability to represent lognormally distributed repair times should be a rather simple future improvement to TIGER. The provisioning models shold also be examined to see if lognormal repair times could be used in these models. This could also be implemented into future or existing availability based inventory models.

The final limitation of TIGER deals with it's input data file preparation. This process is very tedious, difficult, and not user friendly, especially for complex systems. An important future effort should be to develop a menu driven pre-processor to assist the user in creating the TIGER input file.

Changes also need to be made in the SEASCAPE program to permit automatic adjustment of inventory levels to meet budget constraints. Manual adjustment of the allocation index (AI) value to control budget levels is a very slow process and requires considerable computer time.

Comparison of inventory model effectiveness must be done with some reservations. All three models assume steady-state inventory flows. Different results may occur if surge demands or cyclic patterns are introduced into the simulation.

Perhaps the most important recommendation for future research involves additional comparisons of the performance of LEO, ACIM and SEASCAPE. Additional research needs to be done to determine what effects alternate equipment configurations, types of equipment and scenarios have on the effectiveness of the provisioning models.

APPENDIX A. STOCK LEVELS FOR VARIABLE BUDGET ANALYSIS

Table 8. SEASCAPE STOCK LEVELS FOR VARIABLE BUDGET (SERIES)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
60.99%	$414,950	3	4	2	1	3	2	2	3
77.15%	$524,890	4	4	2	1	5	2	2	3
86.60%	$589,190	4	4	2	2	5	3	3	3
94.86%	$645,420	4	5	2	2	6	3	3	4
100.00%	$680,450	5	5	2	2	6	3	3	4
105.71%	$719,210	5	5	2	2	6	3	4	4
112.77%	$767,260	5	5	3	2	7	3	4	4
117.91%	$802,200	6	5	3	2	7	3	4	4

Table 9. SEASCAPE VARIABLE BUDGET STOCK LEVELS (PARALLEL)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
61.29%	$416,970	2	2	2	2	3	3	3	3
76.81%	$522,600	2	3	3	2	4	3	4	4
87.66%	$596,390	3	3	3	2	4	3	5	4
91.40%	$621,840	3	3	3	3	4	4	5	4
98.54%	$670,450	4	3	3	3	4	4	5	4
104.05%	$707,950	4	4	3	3	5	4	5	4
112.06%	$762,410	4	4	4	3	5	4	6	5
117.20%	$797,350	5	4	4	3	5	4	6	5

Table 10. LEO STOCK LEVELS FOR VARIABLE BUDGET (SERIES)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
60.83%	$413,830	3	7	2	2	3	3	0	5
79.11%	$538,840	3	7	3	2	5	3	1	5
86.25%	$586,840	4	8	3	2	5	3	1	5
92.28%	$627,860	4	8	3	2	6	4	1	5
98.00%	$666,710	4	8	3	2	6	4	2	5
103.13%	$701,650	5	8	3	2	6	4	2	5
110.65%	$752,820	5	9	3	2	7	4	2	5
115.79%	$787,760	6	9	3	2	7	4	2	5

Table 11. LEO STOCK LEVELS FOR VARIABLE BUDGET (PARALLEL)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
59.68%	$406,070	0	0	3	3	2	4	5	5
77.98%	$530,470	0	0	4	3	4	4	6	5
84.00%	$571,490	0	0	4	3	5	5	6	5
89.51%	$608,990	0	0	4	3	6	5	6	5
100.73%	$685,340	0	0	4	3	7	5	7	5
106.24%	$722,840	0	0	4	3	8	5	7	5
111.95%	$761,690	0	0	4	3	8	5	8	5
117.47%	$799,190	0	0	4	3	9	5	8	5

Table 12. ACIM STOCK LEVELS FOR VARIABLE BUDGET (SERIES)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
62.20%	$423,170	3	3	1	1	4	2	2	2
77.15%	$524,890	4	4	2	1	5	2	2	3
86.08%	$585,670	4	4	2	2	5	2	3	3
92.11%	$626,690	4	4	2	2	6	3	3	3
99.26%	$675,300	5	5	2	2	6	3	3	3
104.97%	$714,150	5	5	2	2	6	3	4	3
112.77%	$767,260	5	5	3	2	7	3	4	4
117.91%	$802,200	6	5	3	2	7	3	4	4

Table 13. ACIM STOCK LEVELS FOR VARIABLE BUDGET (PARALLEL)

		Stock Level by Part Type							
% Benchmark	Inventory Cost	1	2	3	4	5	6	7	8
61.98%	$421,670	2	1	1	2	4	2	3	2
76.29%	$519,080	2	3	3	2	4	2	4	4
87.14%	$592,870	3	3	3	2	4	2	5	4
91.40%	$621,840	3	3	3	3	4	4	5	4
98.54%	$670,450	4	3	3	3	4	4	5	4
104.05%	$707,950	4	4	3	3	5	4	5	4
112.06%	$762,410	4	4	4	3	5	4	6	5
117.20%	$797,350	5	4	4	3	5	4	6	5

APPENDIX B. STOCK LEVELS FOR VARIABLE MSRT ANALYSIS

Table 14. ACIM STOCK LEVELS FOR VARIABLE MSRT

		Stock Level by Part Type							
MSRT (days)	Inventory Cost	1	2	3	4	5	6	7	8
12	$548,170	4	4	2	2	4	2	3	3
17.5	$563,740	4	4	2	1	5	2	3	3
24	$563,740	4	4	2	1	5	2	3	3
30	$563,740	4	4	2	1	5	2	3	3
36	$562,390	4	4	2	1	6	2	2	3
41	$576,060	4	5	2	1	6	2	2	3

Table 15. LEO STOCK LEVELS FOR VARIABLE MSRT

		Stock Level by Part Type							
MSRT (days)	Inventory Cost	1	2	3	4	5	6	7	8
12	$547,140	4	5	2	1	5	3	2	4
17.5	$573,170	4	7	3	2	5	3	1	5
24	$566,200	3	11	4	3	4	5	0	7
30	$553,860	2	16	5	3	2	6	0	10
36	$566,970	1	21	6	4	0	8	0	13
41	$573,090	0	21	7	5	0	9	0	14

Table 16. SEASCAPE STOCK LEVELS FOR VARIABLE MSRT

		Stock Level by Part Type							
MSRT (days)	Inventory Cost	1	2	3	4	5	6	7	8
12	$563,740	4	4	2	1	5	2	3	3
17.5	$567,260	4	4	2	1	5	3	3	3
24	$585,990	4	5	2	1	5	3	3	4
30	$570,420	4	5	2	2	4	3	3	4
36	$570,420	4	5	2	2	4	3	3	4
41	$560,850	4	6	3	2	4	3	2	5

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